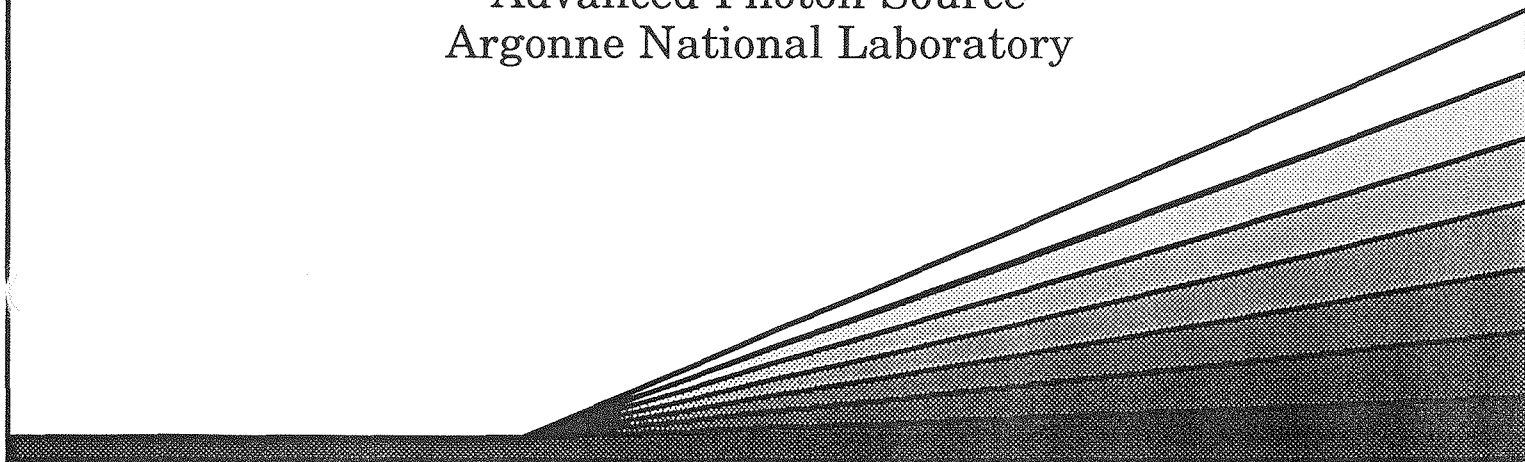


# Feasibility of Using a High Power CO<sub>2</sub> Laser as an Alternative Source to Test High Heat Load X-ray Optics

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## Introduction

The proposed Undulator A at the Advanced Photon Source (APS) will deliver peak power densities of 150 watts/mm<sup>2</sup>, with total power up to 3800 watts, incident on the first crystal of a double crystal monochromator. The XFD-OP group has undertaken an extensive research program to find efficient methods to dissipate the resulting high heat loads while preserving the diffracting characteristics of the first crystal.

Testing of the cooled optics is an integral part of the research effort. Present synchrotron radiation sources can provide neither sufficient power nor power density to perform tests under conditions similar to the expected output of Undulator A. For example, prototypes for the cooled first crystal have been tested at CHESS [1] with 379 watts of power and a peak power density of 48 watts/mm<sup>2</sup>, and at NSLS [2] with 38 watts total power and 118 watts/mm<sup>2</sup>. No synchrotron radiation source currently in operation can achieve the combination of total power and power density expected at the APS undulator beamlines.

We have studied the possibility of using a high power carbon dioxide laser as an alternative heat load source to test cooled x-ray optics. The CO<sub>2</sub> laser at the Laser Applications Laboratory (LAL) at ANL has an output power from 800 to 6700 watts. The focusing optic can be selected to achieve different laser beam sizes; one of the available integrating lenses produces a 4 mm by 4 mm beam spot, with power densities as high as 400 watts/mm<sup>2</sup>. This laser has been successfully used for testing APS beamline front end components that will also be subject to large heat loads.

The main question to be answered is whether the power deposition profile for the laser in silicon can be adjusted to resemble that of x-ray absorption. At the CO<sub>2</sub> laser wavelength of 10.6 microns, the absorption coefficient in silicon (N-type, resistivity  $\rho = 1 \Omega\text{cm}$ ) is 0.2 cm<sup>-1</sup> [3] (see Figure 1). In contrast, the 1/e absorption length for the undulator x-ray beam incident on the first crystal of the monochromator is approximately 20 cm<sup>-1</sup>; at typical diffraction angles ( $\theta_B = 10\text{-}20$  degrees), practically all of the x-ray absorption occurs in the top 1-mm layer of the silicon

crystal. A meaningful test of the cooled x-ray optic requires that the absorption depth for the laser power be similar to that of x-rays so that the parameters for heat transfer and surface distortion are comparable.

Both the absorption coefficient for 10.6-micron radiation in silicon and the resistivity vary with the dopant concentration. As the dopant concentration increases, so does the free carrier concentration, the resistivity drops, and the absorption coefficient for CO<sub>2</sub> laser light increases [3,4]. In principle it should be possible to select a silicon crystal with low resistivity, that is, high dopant concentration, such that the laser absorption profile resembles that of x rays.

To determine the feasibility of using the CO<sub>2</sub> laser at LAL as an alternative heat source for x-ray optics tests, we have studied the absorption of the 10.6-micron laser light in silicon for two different dopant concentrations, using the resistivity as a predictor for the absorption length. We describe the results from these tests in this report.

## Experiments

We performed two sets of experiments at LAL. Figure 2 shows a schematic diagram of the setup for both runs. The CO<sub>2</sub> laser impinged vertically on a 1.6-mm-diameter, water-cooled copper aperture and was then normally incident on the silicon test piece. A copper cube, 12.5 mm on a side, was located under the silicon piece and acted as a calorimeter for the transmitted power. The laser power was typically 600 to 800 watts, while the power transmitted through the water-cooled aperture was in the range of 1.3 to 1.7 watts. One thermocouple was attached to the silicon and one to the copper cube. By measuring the change in temperature as a function of time, and, using the known specific heat and mass, we determined the power deposited in the silicon and in the copper. The maximum temperature attained was in the range of 45 to 85°C for the different silicon samples and 65°C for the copper mass. At these temperatures, radiation losses could be neglected, and only convection losses had to be taken into account. From data taken with and without the silicon in place, we determined the power absorbed, transmitted, and incident on the crystal.

In September 1992, we measured the power absorbed in N-type, phosphorus-doped silicon as a function of thickness. The resistivity of the silicon was  $0.19 \pm 0.02 \text{ } \Omega\text{cm}$ , measured using the four point probe method, and is in good agreement with the nominal 0.13-0.19  $\Omega\text{cm}$  range specified by the manufacturer. We fabricated five 6 mm by 30 mm silicon test pieces with thicknesses ranging from 0.74 mm to 15.39 mm, and we

measured the power absorbed and transmitted by each of them. The top and bottom surfaces were polished; no etching was performed. Figure 3 shows the ratio of absorbed to transmitted power as a function of sample thickness. The fit to the data includes the reflection at the crystal surfaces and the absorption in the crystal. We obtained a reflection coefficient  $\beta=46\pm12\%$ , and a free carrier absorption coefficient  $\alpha=2.09\pm0.26\text{ cm}^{-1}$ , in good agreement with the expected values of 30% [4] and 2 to 3  $\text{cm}^{-1}$ [3], respectively. These tests verified that the resistivity is a good predictor for the free carrier absorption coefficient.

The x-ray beam from Undulator A will be absorbed in a 1 mm layer of silicon. To achieve a similar deposition for the CO<sub>2</sub> laser beam in normal incidence, we need N-type material with a 1/e absorption length of approximately 50  $\text{cm}^{-1}$ . The required resistivity lies in the range of 0.02-0.03  $\Omega\text{cm}$ , with a corresponding phosphorus dopant concentration of approximately  $10^{18}\text{ cm}^{-3}$ . We procured silicon with nominal resistivity in this range, and fabricated a 0.16-mm-thick wafer. Both sides were polished, but the wafer was not etched. In February 1993, we measured the fraction of the laser power absorbed in the wafer using the same setup described above. The resulting reflection coefficient was  $\beta=48\pm4\%$ , and the absorption coefficient was  $\alpha=16\pm5\text{ cm}^{-1}$ . The discrepancy between the measured and predicted values for  $\alpha$  was resolved when an in-house measurement of the resistivity yielded  $\rho=0.071\pm0.007\text{ }\Omega\text{cm}$ . Using this value for the resistivity, the prediction for  $\alpha$  is in the range 13-17  $\text{cm}^{-1}$ , see (Figure 1) in very good agreement with the experimental result.

## Discussion

The tests at LAL have demonstrated that it is possible to deposit a significant fraction of the CO<sub>2</sub> laser power in a thin silicon layer. For example, using the material with  $\rho=0.071\text{ }\Omega\text{cm}$  and the laser in normal incidence, we could couple 52% of the power into the silicon, and, of this fraction, 90% would get absorbed in the first 1-mm layer. If we chose to use the 4 mm by 4 mm integrating optic for the laser, we could achieve a heat load of 215 watts/ $\text{mm}^2$ , with 3440 watts of total power.

A cooled crystal fabricated with low-resistivity silicon, in conjunction with the high power laser, could be used to test different aspects of the cooling mechanism. For example, the total power that can be coupled into the crystal would test the ability of the heat exchanger to dissipate large heat loads. By using an infrared camera to record temperatures on the crystal, we can assess the efficiency of the cooling mechanism to remove the heat from the surface of the crystal. The

temperature pattern could also be used to check the results of finite element analysis calculations performed using the known laser beam profile as input.

The x-ray diffraction characteristics of the silicon crystal under large heat loads provide the only conclusive test of the performance of the cooling mechanism. The ideal testing setup would include an x-ray tube at the laser location to measure the diffraction while the laser is impinging on the cooled crystal. Even then, other concerns may render the result of such a test inconclusive. The high dopant concentration required to effectively couple the laser power into the silicon crystal may change the thermal properties of the silicon, for example, the thermal conductivity or the thermal expansion coefficient, in such a way that comparing the measurements performed on a low-resistivity and an intrinsic silicon crystal may be difficult.

A much more desirable testing scenario is to develop a high power and high power density x-ray source. Such an effort is currently underway: a plan is being implemented to install a focusing mirror at a wiggler beamline at CHESS. This mirror would deliver 1000 watts of total power and 200 watts/mm<sup>2</sup> on the first crystal of the monochromator, thus providing a more accurate test of the cooling scheme.

The imminent availability of a high power and high power density x-ray source, coupled with the technical complications involved in performing an x-ray diffraction test at the Laser Applications Laboratory, make the high power laser alternative less appealing at this time. In spite of its shortcomings, we should keep in mind that the possibility exists to use the CO<sub>2</sub> laser as an alternative high heat load source for testing cooled x-ray optics.

## **Acknowledgments**

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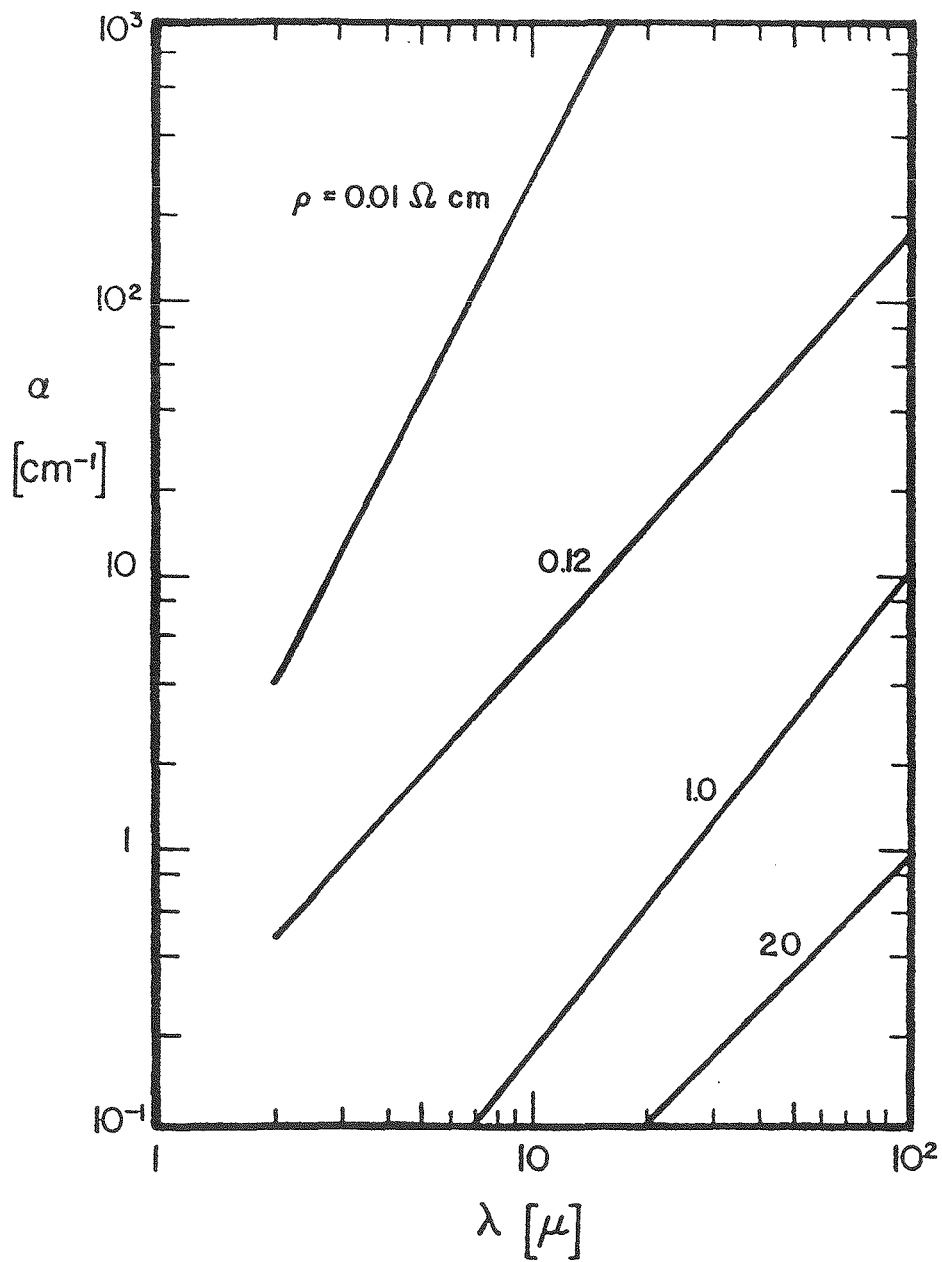


FIGURE 1: Free carrier absorption coefficient  $\alpha$  as a function of wavelength  $\lambda$  (in microns) and resistivity  $\rho$ . From *Silicon Semiconductor Data*, by H.F. Wolf [3].

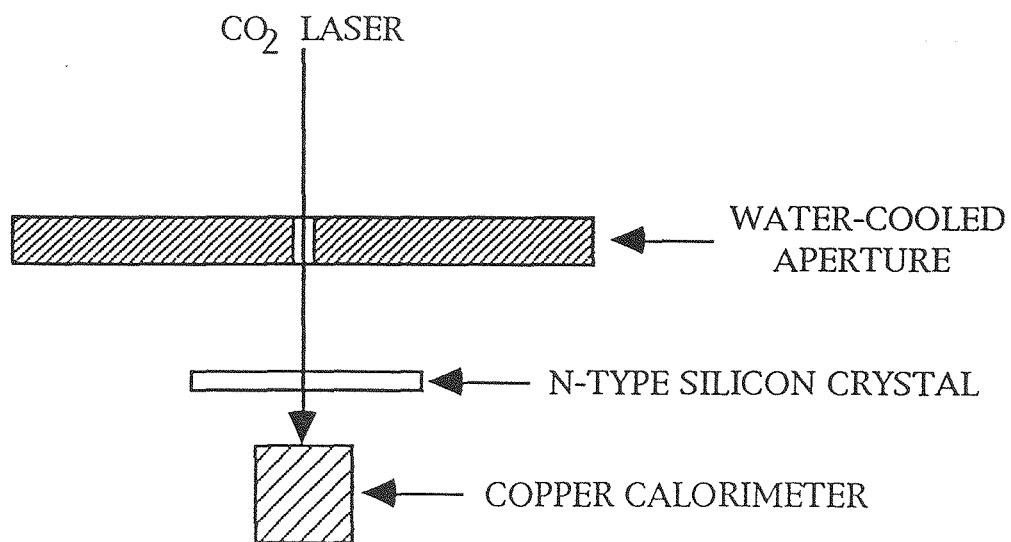


FIGURE 2: Schematic diagram of the setup for the transmission tests at the Laser Applications Laboratory.



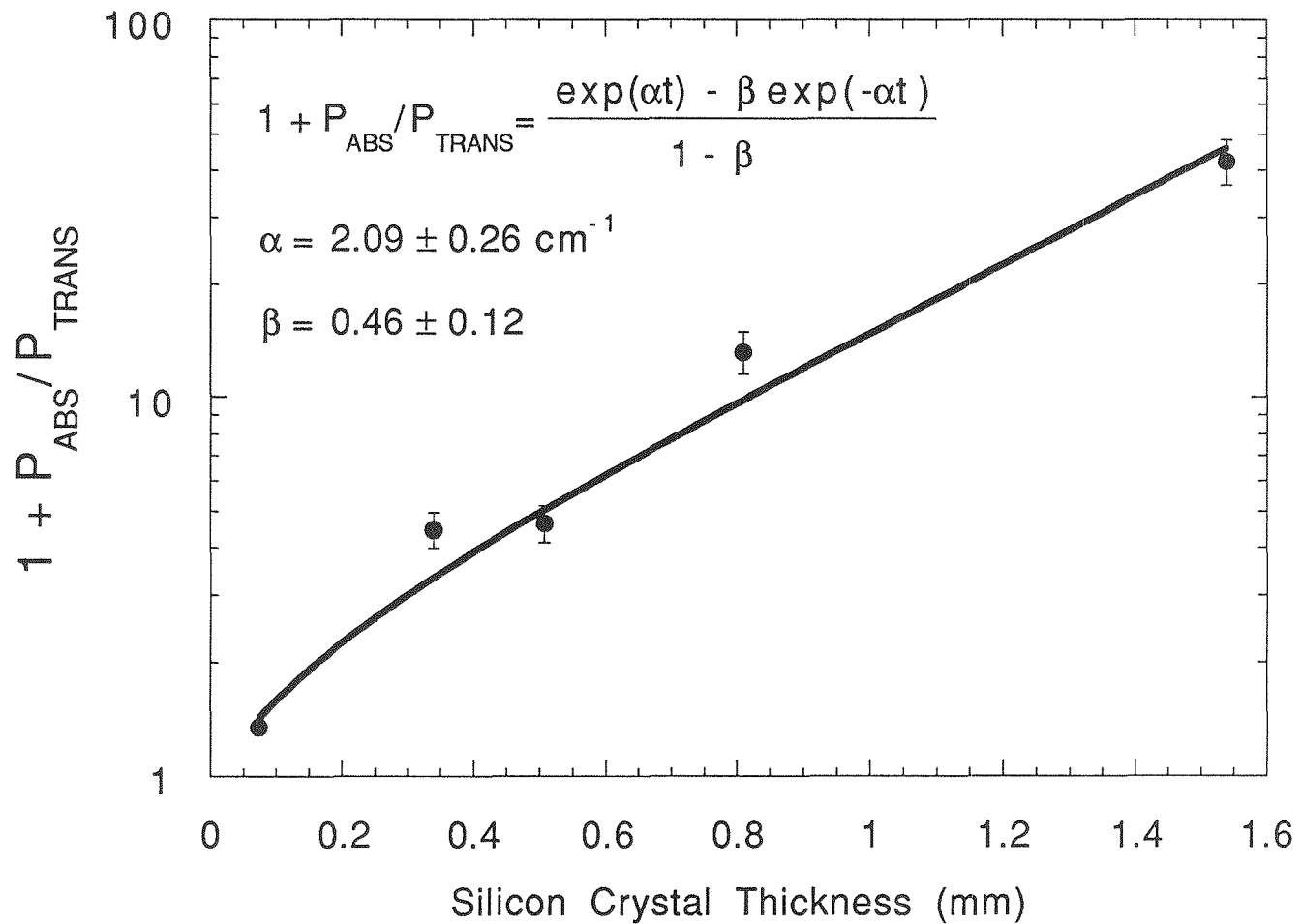


FIGURE 3: Ratio of absorbed to transmitted power as a function of the thickness of the silicon sample. The resistivity of the N-type silicon was  $\rho = 0.19 \text{ } \Omega\text{cm}$ ; the  $\text{CO}_2$  laser wavelength is  $\lambda = 10.6 \text{ } \mu\text{m}$ .